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EXPLORING DISJUNCTIVE PLANNING AS A MEANS TO SCALE-UP PLAN SYNTHESIS

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EXPLORING DISJUNCTIVE PLANNING AS A MEANS TO SCALE-UP PLAN SYNTHESIS

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13. ABSTRACT *(Maximum 200 words)*

In this research, we have concentrated on exploring the advantages of disjunctive plan representations in improving planning performance. The results of the research included: 1) development of a system called GP-CSP, which uses direct constraint satisfaction techniques to solve the planning graph of Graphplan; 2) development of a method where the distance heuristics that were originally developed as part of the heuristic state search community can be applied to the backward search of Graphplan, a disjunctive planner; and 3) evaluation of the utility of different types of mutex propagation routines in the context of SAT and CSP encodings of the automated planning problems. The results of this research have been disseminated to the planning community through three publications in the 5th International Conference on Artificial Intelligence Planning Scheduling and one publication in the 2000 National Conference on Artificial Intelligence.

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Exploring Disjunctive Planning as a means to scale-up Plan Synthesis: Final Report on AFRL F20602-98-1-0182

1 Executive Summary

In this research, we have concentraed on exploiting the advantages of disjunctive plan representations in improving planning performance. The following are three of the important results of this research, all of which were published in the proceedings of the International Conference on AI Planning and Scheduling Systems:

- We developed a system called GP-CSP, which uses direct constraint satisfaction techniques to solve the planning graph of Graphplan. This system allowed us to closely study the impact of CSP representations and constraint propagation techniques, variable and value ordering techniques on the performance of the planner. This work has been presented at AIPS-2000, and has recently been submitted to Artificial Intelligence Journal. URLs for the GP-CSP system is: http://rakaposhi.eas.asu.edu/gp-csp.html
- We developed a method where by the distance heuristics that were originally developed as part of the heuristic state search community can be applied to the backward search of Graphplan, a disjunctive planner. Our work lead to a version of Graphplan that is significantly faster than the original Graphplan algorithm. A paper on this work was published in the proceedings of AIPS-2000.
- We also evaluated the utility of different types of mutex propagation routines in the context of SAT and CSP encodings of the automated planning problems. This work allowed us to settle the question as to the true impact of the mutex propagation routines on the SAT encodings. The results of this work have been published at AIPS-2000.

The research results summarized above have also lead us to some very significant follow-on efforts.

- The work on distance-based variable ordering techniques for Graphplan has eventually lead us to develop the AltAlt system, which cleverly complements the relative advantages of Graphplan and state-space search systems. AltAlt uses the Graphplan's Planning graph to derive very high quality heuristics that are used to focus the search of a backward state search planner. As such, AltAlt effectively integrates the ideas of conjunctive and disjunctive planners. Papers based on the AltAlt sytem have been presented at AAAI-2000 and KBCS-2000. A longer journal submission based on this work has recently been accepted to the Aritificial Intelligence Journal. The URL for the AltAlt page is http://rakaposhi.eas.asu.edu/altweb/altalt.html

- The work on the CSP encodings for partial order planning has lead to the RealPlan system, which attempts to integrate planning and scheduling functions in a loosely integrated architecture. Specifically, since most approaches to scheduling are already based on CSP encodings, we were able to provide an effective integration using the GP-CSP system, which does planning using CSP. The resulting system, called RealPlan, has been shown to be able to scale up better than monolithic planners, in domains where one has both causal and resource reasoning components. This work has been published in AAAI-2000 and a longer paper on it has been accepted to the Artificial Intelligence Journal. The URL for the AltAlt page is at http://rakaposhi.eas.asu.edu/realplan.html

2 Abstracts of the relevant papers

This section lists the abstracts of the papers that directly resulted from the research supported by this grant.

Planning as Constraint Satisfaction: Solving the planning graph by compiling it into CSP

The idea of synthesizing bounded length plans by compiling planning problems into a combinatorial substrate, and solving the resulting encodings has become quite popular in recent years. Most work to-date has however concentrated on compilation to satisfiability (SAT) theories and integer linear programming (ILP). In this paper we will show that CSP is a better substrate for the compilation approach, compared to both SAT and ILP. We describe GP-CSP, a system that does planning by auto- matically converting Graphplan's planning graph into a CSP encoding and solving it using standard CSP solvers. Our comprehensive empirical evaluation of GP-CSP demonstrates that it is superior to both Blackbox system, which compiles planning graphs into SAT encodings, and ILP-based planner in a wide range of planning domains. Our results show that CSP encodings outperform SAT encodings in terms of both space and time requirements in various problems. The space reduction is particularly important as it makes GP-CSP less susceptible to the memory blow-up associated with SAT compilation methods. The paper also discusses various tech- niques in setting up the CSP encodings, planning specific improvements to CSP solvers, and strategies for

variable and value selection heuristics for solving the CSP encodings of different types of planning problems.

Distance-based Goal-ordering techniques for Graphplan

It has been observed in the literature that the backward search of Graphplan algorithm can be seen as solving a dynamic CSP problem. Given this relation, the order in which the backward search considers goals for expansion–the so-called "variable ordering heuristic", and the order in which the actions supporting those goals are considred – i.e., the "value ordering heurstic"–can have a very significant impact on Graphplan's performance. Despite this expectation, experiments with the traditional CSP variable ordering strategies such as "most constrained variable first" and "least constrained value first"–have been shown to be of at best marginal utility. In this paper, we propose a class of variable and value ordering strategies that are based a notion of the difficulty of achieving the corresponding subgoal. The difficulty of achievement is quantified by the first level of the planning-graph at which that subgoal appears. We will argue that these are better suited to the dynamic CSP problem addressed by Graphplan's backward search. We backup our arguments by empirical studies that demonstrate that our heuristics lead to orders of magnitude improvement in Graphplan's backward search. We will end with a discussion of the relations between this heuristic and the distance based heuristics used by UNPOP and HSP planners.

Investigating the Effect of Relevance and Reachability Constraints on SAT Encodings of Planning

Currently, Graphplan and Blackbox, which converts Graphplan's plan graph into the satisfaction (SAT) problem, are two of the most successful planners. Since Graphplan gains its efficiency from the forward propagation of reachability based mutual exclusion constraints (mutex) and their backward use, it has been believed that SAT encoding will also benefit from mutexes. In this paper, we will try to answer two important questions: (1) Are mutual exclusions actually useful for solution extraction in SAT encoding? (2) Are there other useful constraints that can be propagated on the planning graph which may help SAT solvers? Our experiments with systematic solvers Relsat and Satz shows that though forward mutexes are useful in general, there are domains in which mutex constraints can slow down search. More over, we introduce the notion of backward mutex and their propagation which is based on relevance analysis and implement it in Blackbox. We find that the addition of relevance based backward mutual exclusions helps speedup the Relsat solver in solving the SAT encoding of many standard planning problems.

RealPlan: Loosely Coupled Architectures for Integrating Planning and Scheduling

In most real-world reasoning problems, planning and scheduling phases are loosely coupled. For example, in project planning, the user comes up with a task list and schedules it with a scheduling tool like Microsoft Project. One can view automated planning in a similar way in which there is an action selection phase where actions are selected and ordered to reach the desired goals, and a resource allocation phase where enough resources are assigned to ensure the successful execution of the chosen actions. On the other hand, most existing automated planners studied in Artificial Intelligence do not exploit this loose-coupling and perform both action selection and resource assignment employing the same algorithm. The current work shows that the above strategy severely curtails the scale-up potential of existing state of the art planners which can be overcome by leveraging the loose coupling.

Specifically, a novel planning framework called `RealPlan` is developed in which resource allocation is de-coupled from planning and is handled in a separate scheduling phase. The scheduling problem with discrete resources is represented as a Constraint Satisfaction Problem (CSP) problem, and the planner and scheduler interact either in a master-slave manner or in a peer-peer relationship. In the former, the scheduler simply tries to assign resources to the abstract causal plan passed to it by the planner and returns success. In the latter, a more sophisticated "multi-module dependency directed backtracking" approach is used where the failure explanation in the scheduler is translated back to the planner and serves as a *nogood* to direct planner search.

`RealPlan` not only preserves lboth the correctness as well as the quality (measured in length) of the plan but also improves efficiency. Moreover, the failure-driven learning of constraints can serve as an elegant and effective approach for integrating planning and scheduling systems. Beyond the context of planner efficiency, the current work can be viewed as an important step towards merging planning with real world problem solving where plan failure during execution can be resolved by undertaking only necessary resource re-allocation and not complete re-planning.

Publications that acknowledge this grant

1. Extracting effective and admissible heuristics from the planning graph. X. Nguyen and S. Kambhampati. AAAI 2000. (Acceptance ratio: 30

2. M. Do and S. Kambhampati. Solving Planning Graph by Com- piling it into a CSP. Proc. 5th AIPS. 2000. (Acceptance ratio: 30

3. S. Kambhampati and R. Nigenda. Distance-based goal order- ing heuristics for Graphplan. Proc. 5th AIPS 2000. (Poster. Acceptance ratio: 40

4. M. Do, B. Srivastave and S. Kambhampati. Investigating the effect of Relevance and Reachability COnstraints on SAT encodings of Planning. Proc. 5th AIPS 2000. (Poster. Acceptance ratio: 40

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